

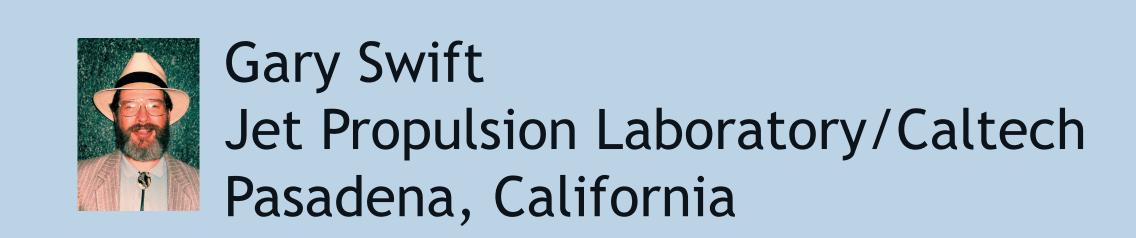


Complex Upset Mitigation Applied to a Re-configurable Embedded Processor



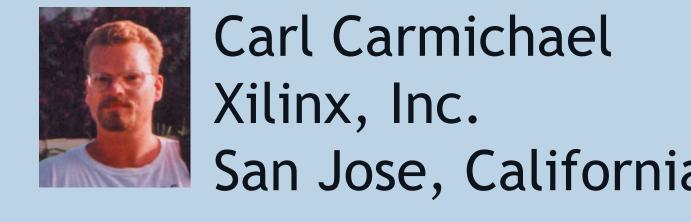


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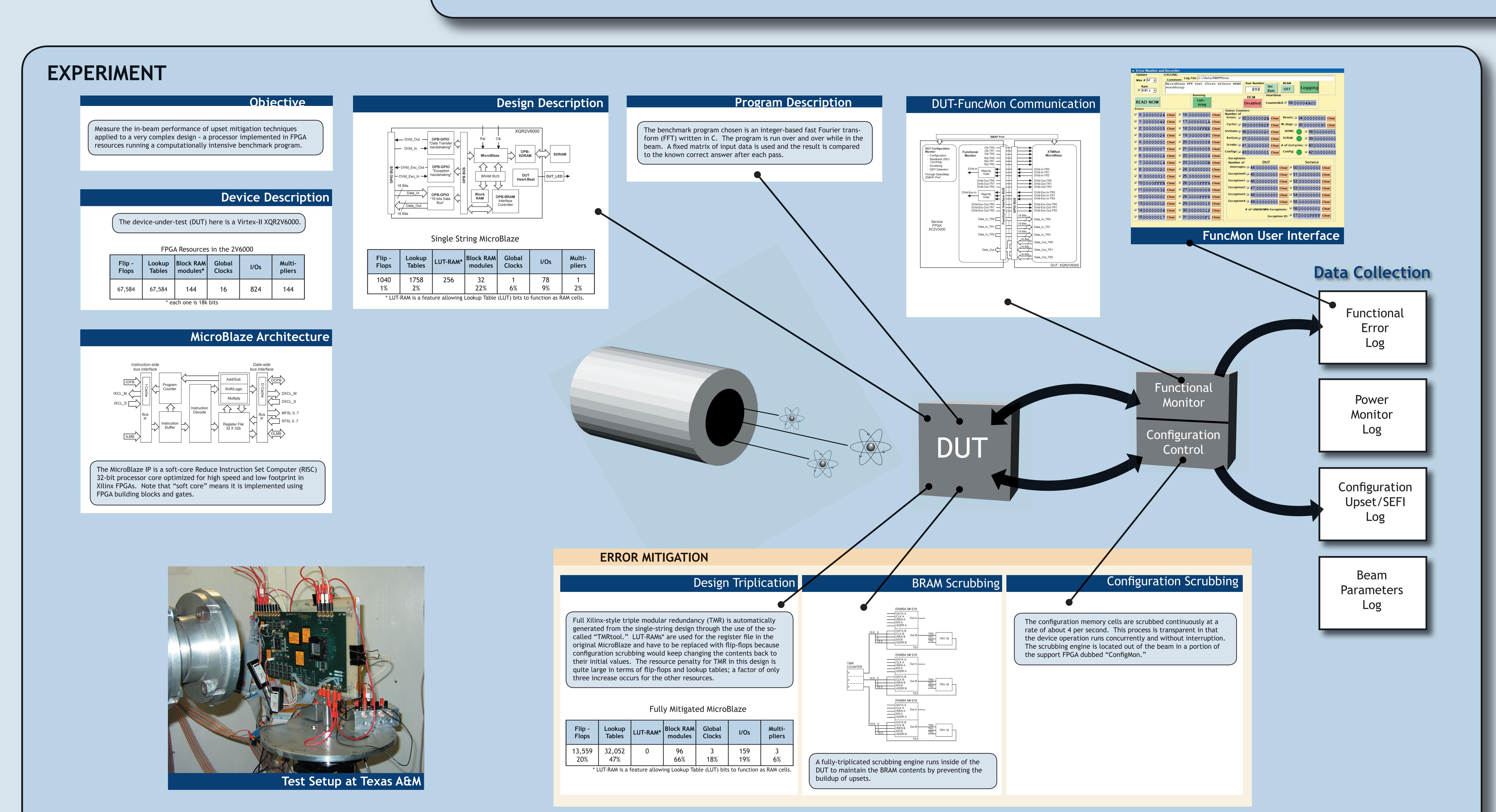


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RESULTS

Results here are for irradiations with 63 MeV protons conducted at the UC-Davis cyclotron.

The errors observed were categorized as:

Type 1 - FFT program calculates an incorrect result Type 2 - MicroBlaze communication sequence is wrong or stops (timeout)

Type 3 - An exception or interrupt is called Error recovery occurred in three cases: (a) the next iteration of the program, (b) when the processor was reset, or (c) after scrubbing the FPGA logic. For some errors, none of these actions recovered correct program operation, a condition dubbed "Runaway" and signified with the suffix '-R.' Thus, Type 1-R is "Runaway Wrong Answers" and Type 2-R is "Runaway Resets." These errors require reconfiguration of the FPGA to recover correct program operation. Reconfiguration includes reloading the program (all three copies) into the FPGA's BRAM. Note that beam-induced exceptions and interrupts almost always result in "Reset Runaway."

Cross Sections for Proton-Induced Errors Categorized by Type

DDAM Carubbar	Flux [p/cm²/s]	CLB Upsets per scrub	Fluence [p/cm²]	Error Cross Section [cm ²]				
BRAM Scrubber				Type 1	Type 1-R	Type 2	Type 2-R	Type 3-R
OFF	1.9 x 10 ⁷	2 to 7	9.8 x 10 ¹⁰	7.6 x 10 ⁻¹⁰	2.0 x 10 ⁻¹¹	6.3 x 10 ⁻¹⁰	1.4 x 10 ⁻¹⁰	8.2 x 10 ⁻¹¹
OFF	3.9×10^7	4 to 15	2.5 x 10 ¹⁰	8.4 x 10 ⁻¹⁰	< 4.0 x 10 ⁻¹¹	6.0 x 10 ⁻¹⁰	2.0 x 10 ⁻¹⁰	1.6 x 10 ⁻¹⁰
	1.7 x 10 ⁷	2 to 7	1.0 x 10 ¹¹	7.0 x 10 ⁻¹¹	< 1.0 x 10 ⁻¹¹	5.0 x 10 ⁻¹¹	< 1.0 x 10 ⁻¹¹	< 1.0 x 10 ⁻¹¹
ON	1.7 x 10 ⁸	15 to 30	1.0 x 10 ¹¹	2.9 x 10 ⁻¹⁰	1.0 x 10 ⁻¹¹	2.1 x 10 ⁻¹⁰	7.0 x 10 ⁻¹¹	< 1.0 x 10 ⁻¹¹
	1.7 x 10 ⁹	150 to 190	4.9 x 10 ¹⁰	1.1 x 10 ⁻⁹	< 2.1 x 10 ⁻¹¹	7.8 x 10 ⁻¹⁰	1.7 x 10 ⁻¹⁰	4.1 x 10 ⁻¹¹

Cross Section Comparison: Runaway Resets and Projected Code Corruption (Scrubber ON)

Flux	Error Cross S	Ratio		
[p/cm²/s]	Runaway Resets	Code in BRAM	(Resets: BRAM)	
1.7 x 10 ⁸	6.8 x 10 ⁻¹¹	1.2 x 10 ⁻¹¹	5.6:1	
1.7 x 10 ⁹	1.7 x 10 ⁻¹⁰	0.38 x 10 ⁻¹⁰	4.3:1	

Portion of Runaway Resets Accompanied by Exceptions

BRAM Scrubber	Flux [p/cm²/s]	Fluence [p/cm²]	Runaway Resets [#]	With Exceptions [#]
OFF	1.9 x 10 ⁷	9.8 x 10 ¹⁰	14	9
OFF	3.9×10^{7}	2.5 x 10 ¹⁰	5	4
	1.7 x 10 ⁷	1.0 x 10 ¹¹	0	0
ON	1.7 x 10 ⁸	1.0 x 10 ¹¹	7	0
	1.7 x 10 ⁹	4.9 x 10 ¹⁰	8	2

Upset mitigation is working very well as only a few errors are observed at high fluence. As expected for a well mitigated design, the error cross sections increase rapidly with increasing flux while the configuration upset rate is directly proportional to flux. As seen in the first Table, scrubbing the BRAM (where the program code resides) decreases the error cross sections by over an order of magnitude for approximately the same flux. This indicates that most of the errors of all types in the unscrubbed case are BRAM corruption due to upset accumulation reaching the point where two of the three copies have upsets in the same bit. This again demonstrates that, for reconfigurable FPGAs, triple modular redundancy needs scrubbing to be really effective. Because the BRAM scrubber's resource cost is quite low, it should not be omitted for flight designs that use BRAMs.

Tests of the BRAM scrubber performance were previously conducted and, through appropriate scaling of those results, the code corruption cross section can be predicted. As seen in the second Table, the expected code corruption can only explain a fraction of the reset runaways even if code corruption always results in a reset runaway (which is not really the case - corruption also results in runaway wrong answers). The Ratio column indicates that code corruption goes up faster with flux than reset runaways do.

A great deal of investigation has gone into understanding the reset runaways, and this work is continuing. The third Table addresses the question of what portion of the reset runaways are accompanied by beam-induced exceptions. With BRAM scrubbing off, exceptions are seen with most of them; the opposite is true with scrubbing on. Thus, one of the main effects of scrubbing the BRAM is the reduction of beam-induced exceptions.

Projecting flux down to space environment rates, the error rate for the mitigated MicroBlaze is less than the device SEFI rate; this is the hallmark of successful upset mitigation.